Discerning shifting irrigation practices from passive microwave radiometry over Punjab and Haryana

ABSTRACT

Overexploitation of groundwater (GW) in the recent past is a well-known fact for the Punjab and Haryana region of India, as reported by several studies using satellite-based gravity anomaly from the Gravity Recovery and Climate Experiment mission and also by using observed data. This decline in GW has enforced the Punjab Preservation of Sub-Soil Water Act 2009, and resulted in change in rice irrigation practices over the study region. In this study, a shifting pattern of irrigation practices has been detected during pre- and post-Water Act using high temporal passive microwave radiometer (Advanced Microwave Scanning Radiometer – Earth Observing System, AMSR-E) and optical data. Multi-year soil moisture data for the period May to September were analysed for the years 2002 to 2011. A shift in the early soil wetness pattern has been observed during 2002 to 2011 in most of the study region. The overall delay in irrigation practices was observed to be 10 ± 4 days over Punjab and Haryana in the pre- and post-Water Act implementation. Multi-temporal passive microwave radiometry was found to be expedient for observing the dynamic pattern of irrigation/agricultural practices over Punjab and Haryana states.

Key words | AMSR-E, irrigation, passive microwave, soil moisture, water conservation policy, water resource management

INTRODUCTION

The hydrological cycle in any landscape is constituted mainly by three components: (1) water input, (2) water output and (3) water storage (Sass & Creed 2011). Among them, the ‘water storage component’ is considered the most essential component for many geophysical and biophysical processes. The water storage component includes soil moisture, which is dynamic in nature and is the most essential element of water resource management practices as it affects the water cycle of the atmosphere, earth surface and subsurface (Kim et al. 2015). Quantitative spatiotemporal information related to soil moisture content in different strata of the soil profile may prove to be an effective way of implementing management practices (Pietroniro et al. 2005) both at local as well as regional scale. Soil moisture content peaks in the rainy season (June-September) and remains low before and after that. In agricultural practice, as soil moisture increases, vegetation also starts growing and follows the phenological cycle. In the case of rice crop, soil moisture remains high until full growth stage and most of the available water is utilized for photosynthesis and growth. The Advanced Microwave Scanning Radiometer – Earth Observing System (AMSR-E) soil moisture product shows synchronization with the rainfall in rain-fed regions (Singh et al. 2005), but it is very low when the satellite viewed area is covered by fully grown vegetation (Oza et al. 2006). However, on ground, the soil moisture remains high for the whole rainy season. The Normalized Difference Vegetation Index (NDVI), an indicator of vegetation growth, displays a similar pattern as shown by soil moisture with some time lag. The temporal profiles
(or trajectories) of rainfall, soil moisture and NDVI remain in synchrony unless there exists some other influencing factors (like anthropogenic activities). However, anthropogenic activities such as irrigation may shift/change this synchronous pattern in terms of days or months especially during the pre-monsoon period (Singh et al. 2005). In such a situation the soil moisture starts increasing even before the onset of monsoon. This type of situation is quite common in irrigated systems like Punjab and Haryana.

The synchronous profiles of rainfall, soil moisture and NDVI get disturbed due to anthropogenic activities, such as changing irrigation practices, and it is an interesting phenomenon in the agricultural landscape. Assessing shifts for these large agricultural regions through ground survey is difficult due to the lack of a network of soil moisture measurements. Satellite remote sensing, such as passive microwave with high temporal resolution, plays an important role in quantitative estimation of soil moisture in the spatiotemporal domain (Singh et al. 2006; Gupta et al. 2011). Brightness temperature measured by passive microwave sensors (radiometer) such as AMSR-E, which have high signal to noise ratio as compared to active microwave sensor (Berger et al. 2005) and have a large coverage area can be used for soil moisture measurement. It has been further proven that soil moisture data derived for a large area using such a methodology is applicable in agricultural- and climate-related studies (Singh et al. 2005; Oza et al. 2006; Gupta et al. 2011) because of its relevance and precision (Al-Yaari et al. 2014). However, limited studies have been attempted on utilizing soil moisture data for the assessment of human-induced changes related to agricultural practices such as irrigation at landscape level.

The current study concerns Punjab and Haryana states of India, which have experienced intensive farming via groundwater (GW) irrigation that has caused a serious depletion in the water table of the areas. As reported in several studies (Vashisht 2008; Tripathi et al. 2016), the timing of the monsoon arrival in Punjab and Haryana is the last week of June and 80% of rainfall occurs in the months of July and September. These areas traditionally are not a rice growing region. However, the regions’ farmers have adopted green revolution strategy and started growing wheat and rice. Rice cultivation in the region started in the mid-1970s, and since then it has intensified continuously, covering more than 22% of the total geographical area of the Punjab and Haryana at present. Punjab alone contributes 11% of the total rice production of the country’s agricultural output and has experienced a more than ten-fold increase in area under rice cultivation since 1966–1967 to 2008–2009 (0.29 Mha and 2.73 Mha, respectively) (Tripathi et al. 2016). Since rice requires more water for growth and production in the whole growing period (ranging from 1,300–1,800 mm) compared to any other crop (Pruitt & Doorenbos 1977; Perven et al. 2012), and the average annual rainfall of the region is much lower (500–700 mm) than that, farmers irrigated the rice crop using both surface and GW resources. Resourceful farmers with an irrigation facility did not depend on the monsoon for rice transplantation and started rice cultivation even before the onset of monsoon (in the month of May and June). This period is relatively hot and dry and irrigated water evaporates at an intense rate (ranging from 5 to 10 mm/day as per model simulation). More water was extracted from the ground (because of drying of surface water resources in the dry season) for irrigation. This resulted in a drastic decrease in GW (Tripathi et al. 2016).

A few remote sensing-based studies have reported this depletion during 2002–2008 using the gravity anomaly data from the Gravity Recovery and Climate Experiment mission (Rodell et al. 2009; Tiwari et al. 2009). Another study conducted by Kaur & Vatta (2015) in the central Punjab also indicated the same issue through ground surveyed data. The GW depletion rate which was 19 cm in the 1980s, reached 25 cm in the 1990s and 91 cm during 2000 to 2005. This triggered a major outcome in the form of governmental policies regarding the conservation of GW resources (such as The Punjab Preservation of Sub-soil Water Act signed on 2 April 2009) in these areas by imposing restrictions on early (pre-monsoon period) cultivation of rice (Singh 2009).

The objective of the present study was to monitor the change in irrigation practices due to implementation of the Water Act (a pre- and post-analysis) and the associated change in the crop growth pattern in the agricultural landscape of Punjab and Haryana states by using passive microwave-based soil moisture and optical remote sensing-based NDVI.
STUDY AREA

Punjab and Haryana states are the major rice cultivation areas located between 73.88° E to 77.60° E longitude and 27.65° N to 32.58° N latitude, and covering an area of 93,682 km². The climate is sub-tropical, semi-arid and monsoonal. Although these states receive less annual rainfall (300–700 mm) compared to the national average (1,100–1,200 mm), they are known for rice production regions at national level. Rice, a water loving crop, requires a large amount of water (1,300–1,500 mm) (Pruitt & Doorenbos 1971; Perveen et al. 2012) for its growth and development which rainfall alone cannot meet. Thus, conjunctive utilization of water (mainly GW and rainfall-based irrigation) is being practised in the region. The region has experienced a large depletion of GW due to overexploitation of water for rice irrigation. Thus, a 2 × 2 cell window of 0.25° × 0.25° spatial resolution each, bounded in between the longitude of 75.50° E to 76.00° E and latitude of 30.50° N to 31.00° N (Figure 1) was selected for the experiment and time series data analysis. Further, the analysis was upscaled for the study area, i.e., Punjab and Haryana.

DATA USED

Passive microwave radiometer soil moisture

Passive microwave radiometer-based soil moisture (spatial resolution 0.25° × 0.25° and temporal resolution every alternate day) from the AMSR-E sensor for the period 2002 to 2011 (May to September, except year 2002 for which data was not available until May 2002) was used. The AMSR-E satellite sensor works in microwave domain and derived soil moisture is available on a website (https://gcom-w1.jaxa.jp/auth.html), by Japan Aerospace Exploration Agency (JAXA). Technical specification of the data and sensor, i.e., AMSR-E, is given in Table 1. The AMSR-E is a passive radiometer, and provides data on global soil moisture with high temporal resolution and relatively finer spatial resolution (Sun et al. 2012). The AMSR-E concept is still functional in the form of a follow-up programme, i.e., AMSR-2 and continuous data availability for the scientific community is ensured along with its capability of confining temporal dynamics related to the soil moisture (Sun et al. 2012; Wanders et al. 2012). It provides data in horizontal-horizontal (HH) and vertical-vertical (VV) polarization mode. The physical model by which soil moisture is retrieved is valid for microwave frequencies up to 10 GHz. At higher frequencies, the scattering from vegetation surfaces dominates and sensitivity of signals to the soil moisture get reduced. Thus, for the soil moisture retrieval, two low frequencies (6.9 and 10.7 GHz) of AMSR-E channels are used. For more detail about the algorithm, readers may refer to Njoku et al. (2003) and Jackson et al. (1999).

Optical data

A NDVI (SPOT-VEG) composite of 10 days, having a spatial resolution of 1 km, made available by Copernicus Global Land Services, was downloaded from the website http://land.copernicus.eu/global/products/ndvi for the year 2002 to 2011. These data were a composite of maximum values of NDVI in a 10-day time frame. Taking a 10-day time period for making the NDVI composite has a unique reason. As the NDVI is the product of optical signals received by SPOT sensor, it is highly affected by cloud cover on a daily basis. It is further considered that the SPOT sensor can cover the whole globe by cloud free data with a 10-day time frame, so taking a 10-day composite is quite reasonable. For a quality NDVI product, basic atmospheric corrections due to molecular scattering are generally considered by the product generation team in the generation phase of the NDVI product, to avoid the atmospheric influence. The effect of aerosol and moisture variation in non-cloudy conditions has an effect on the magnitude of NDVI, but the pattern, which is the focus in the present study, remains the same.

METHODOLOGY

Temporal behaviour of soil moisture, rainfall and NDVI was analysed from May to September spanning from 2002 to 2011. A conceptual scientific explanation of temporal variations of soil moisture, rainfall and NDVI in a rain-fed and irrigated agriculture system was hypothesized. Conceptual trajectories of rainfall, soil moisture and NDVI in rain-fed and irrigated agriculture system are different...
and are shown in Figure 2(a) and 2(b). This synchronization behaviour of temporal profiles of soil moisture, rainfall and NDVI is generally observed in the rain-fed system (Figure 2(b)); however, as there are anthropogenic activities, such as pre-rain irrigation, this synchronous pattern changes showing early soil moisture even before monsoon begins in the case of the irrigated system (Figure 2(a)) (Singh et al. 2005). Figure 2(a) and 2(b) also
show changes in NDVI profiles in both the above discussed agricultural practices. This type of agriculture practice was common in Punjab and Haryana before the implementation of the Water Act. Analysis has been carried out to test the hypothesis through the analysis of AMSR-E soil moisture, SPOT-VEG NDVI and rainfall data in response to the Punjab Water Act. Figure 3 shows a flow diagram of steps followed in the analysis of time series data of SM and NDVI over the study region. A Gaussian model was fitted for soil moisture time series to estimate the Julian day corresponding to first derivative. Similarly, a Gaussian model was also fitted for NDVI time series to estimate the Julian day corresponding to peak crop stage. The changes in Julian day for both the pre- (2002–2007) and post- (2009–2011) policy scenarios were analysed. Details of the analyses are given below.

**Soil moisture analysis**

Daily soil moisture product was not able to cover the globe completely and some gaps remained at daily temporal resolution. For this purpose, 2 days’ data were stacked in such a manner that the data for the second day only fills the gap in the first day data. This generates soil moisture data in the temporal scale of 2 days. Since the objective was to analyse early soil wetness pattern and shift in response to the 2009 Water Act, we have made two sets of the data representing the soil moisture scenario in pre- (before year 2008) and post- (after year 2008) policy time frame, respectively. Then the analysis was done at two stages: (i) at the pilot area to understand the temporal profiles and (ii) at the state level to see the regional patterns.

At the first stage, year-wise data of the soil moisture were sub-set using a pre-defined boundary of the pilot area (Figure 1). Mean moisture content (mean of four pixels of size $0.25' \times 0.25'$) of the pilot area covering $50 \times 50$ km were computed on each alternate day of the year from May to September for the years 2002 to 2011. Multi-year average soil moisture on each alternate day, obtained from the pilot area and corresponding Julian days were used to prepare a Julian day vs. year figure for the better visualization of soil moisture shift. Measurements (average soil moisture of the pilot area) were analysed separately for pre- and post-policy time frame. Average soil moisture for all the years

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### Table 1 | Sensor characteristics and its technical specification

<table>
<thead>
<tr>
<th>Number of bands and their characteristics</th>
<th>Frequency</th>
<th>Spatial resolution</th>
<th>Swath width</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Sensor Nature</strong></td>
<td><strong>Channel</strong></td>
<td><strong>Band</strong></td>
<td><strong>Width</strong></td>
</tr>
<tr>
<td>AMSR-E Passive radiometer</td>
<td>1. 6.925 GHz</td>
<td>1.6 m</td>
<td>1.6 m</td>
</tr>
<tr>
<td></td>
<td>2. 10.65 GHz</td>
<td>350 MHz</td>
<td>0.34 K</td>
</tr>
<tr>
<td></td>
<td>3. 18.70 GHz</td>
<td>100 MHz</td>
<td>50 km (for band 1 and 2)</td>
</tr>
<tr>
<td></td>
<td>4. 23.80 GHz</td>
<td>100 MHz</td>
<td>50 km (for band 3 and 4)</td>
</tr>
<tr>
<td></td>
<td>5. 36.50 GHz</td>
<td>100 MHz</td>
<td>50 km (for band 5)</td>
</tr>
<tr>
<td></td>
<td>6. 89.00 GHz</td>
<td>100 MHz</td>
<td>50 km (for band 6)</td>
</tr>
</tbody>
</table>

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representing the pre-policy time frame (2002 to 2007) was done for each alternate day. Similar average soil moisture was done for the post-policy time frame (2009 to 2011) also. A second-order Gaussian fit was applied on the average SM of pre- and post-policy time frames and associated Julian days to generate the SM variation profiles. The first derivative of fitted soil moisture was generated and its maximum value (which represents change from dry to completely wet state) was used to discern shifting in the irrigation pattern.

At the second stage, maximum value of soil moisture rate change was computed at state level only for rice cultivated regions, using AMSR-E soil moisture measurements (2002–2011) along with corresponding Julian days for each pixel distributed in the Punjab and Haryana state. Spatially distributed Julian days were analysed on the basis of pre- and post-policy time frame similar to that for the pilot area. The Julian day obtained for the post-policy time frame was subtracted from the Julian day obtained for the pre-policy time frame to get the shift in irrigation practices (Equation (1)):

\[ S = JD_{J} - JD_{i} \]
where $S =$ shift in Julian days, $JD_1 =$ average Julian days of pre-policy time frame and $JD_2 =$ average Julian days of post-policy time frame.

Standard deviation (SD) was taken as uncertainty in irrigation shift estimation. Coefficient of variance was further computed to know the entropy of the early (solely GW) and late (rainfall + GW) irrigated scenarios, i.e., pre- and post-policy implementation time frame. In our case, pre-policy scenario means the region has spatial variability in the start of rice cultivation due to a controlled irrigation system (transplanting mainly driven by GW). However, in an uncontrolled system (post-policy scenario), which is mainly dependent on rainfall with supplementary irrigation (GW), rice cultivation practices will be started more uniformly in the region.

We have also analysed two individual years, 2004 and 2010, separately which represent before and after scenarios of the policy implementation and showing no rain events especially in the pre-monsoon period (140–180 JD). This was done to track the shift of irrigation practices without rainfall influence. In this analysis, we have taken maximum soil moisture change rate and its attainment time (JD) for the pilot as well as for the state level.

Rainfall analysis

Indian Meteorological Department (IMD) rainfall data for the study period were also analysed to remove ambiguity in finding soil moisture shift due to rainfall. These data were generated (by Pai et al. 2014) using observations from 6,955 rain gauge stations distributed over the whole Indian region. Selected rain gauge stations (about 3,950) were interpolated using an inverse distance weighted interpolation (IDW) scheme to prepare gridded rainfall data with a spatial resolution of $0.25 \times 0.25^\circ$ (Pai et al. 2014). The rainfall data had similar resolution as the AMSR-E soil moisture, and thus comparing averages of rainfall and soil moisture is quite reasonable.

Rainfall data were sub-set using the pre-defined boundary of the pilot area. This was further partitioned into two sets representing the pre- and post-policy time frames. Daily average rainfall was calculated for the pilot area, and year vs. the Julian day figure was created to analyse the pattern. Next to this, these average rainfall values of the pilot area were subjected to temporal averaging (2002–2007 for pre- and 2009–2011 for post-policy implementation) to find daily average rainfall for the pre- and
Analysis of relationship between soil moisture and rainfall

Soil moisture is dependent on rainfall and both are positively correlated. To analyse the relationship between soil moisture and rainfall in our study region, we used a small window in the pre-monsoon period (1–18 June) and during the monsoon period (1–18 July) both for pre-policy and post-policy time frames. The average rainfall and soil moisture for the above periods were analysed separately to justify our finding regarding the role of policy implementation in the soil moisture scenario of the region. Simultaneously, we correlated JDs of the onset of effective monsoon (OEM) and maximum soil moisture rate change (SMmax) in pre- and post-policy time frame assuming that both the OEM and SMmax will have high correlation if the soil moisture is only dependent on rainfall. However, if soil moisture is governed by some additional factor like irrigation, the timing of OEM and SMmax will have a relatively low correlation especially in the pre-policy time frame.

OEM is a special criterion by which monsoon arrival is defined by IMD, during a 7-day spell. According to IMD, OEM is decided on the basis of the following three criteria:

1. First day of the week should be rainy day (i.e., minimum rain should be >2.5 mm).
2. Total rainfall in 5 days should be equal to 5× evapotranspiration +10.
3. Out of 7 days in a week at least 4 days should receive rainfall ≥2.5 mm.

ET was taken as 6 mm/day because of the hot and dry conditions of the region.

RESULTS AND DISCUSSION

Year-wise soil moisture analysis

Average soil moisture for a selected 2×2 grid cell of the AMSR-E for every alternate day from 15 May (136 JD) to 30 September (274 JD) for the years 2002 to 2011 was estimated and a Julian day vs. year profile was prepared using a subset, i.e., 140 JD to 230 JD (Figure 4). It can be seen that early soil moisture shows a characteristic pattern of variation.
with a shift towards delay in the early soil moisture detection during 2002 to 2011. A similar trend of shifting in soil moisture was observed in the late season (Figure 4). Passive microwave sensor detects soil moisture until the crop attains 40% vegetation fraction (Oza et al. 2006). Therefore, a shift in the early soil moisture attributed for corresponding delays in attaining the 40% vegetation fraction. A second-order Gaussian fit was applied using Julian days and the average soil moisture (pilot area) data for all the year (equation and coefficients are given in Table 2 along with r and RMSE) to understand the direction of shift during the whole period. For further investigation, the maximum rate of change (first derivative, so that change over the period from dry to wet may be chosen accurately) in soil moisture during 140 to 200 JD was estimated. The Julian day at which the maximum rate change of soil moisture was obtained along with SD for each year (2002–2011) was estimated. It was observed that Julian days for attaining the maximum soil moisture change rate ranges from 163 JD (2002) to 193 JD (2009) with SD ranging from 1 to 6 days.

**Rain-deficient year scenario**

Based on rainfall observations over the pilot area, we have identified 2 years (2004 and 2010) with negligible rainfall contribution for the period (i.e., before 180th JD) where we have observed a shift in the early soil moisture change rate. Another reason behind the selection of these 2 years was that they represent years before and after implementation of the Water Act. Analysing data before and after the Act’s implementation may provide strong evidence in the delay of attaining early soil wetness and thus irrigation practices. Gaussian fitted curves for soil moisture and its change rate in these 2 years, i.e., 2004 and 2010 are shown in Figure 5(a) and 5(b). Comparative analysis of these plots shows a total 17 days’ shift (from 163 JD to

![Soil moisture (%) variations plotted with reference to Julian days (x-axis) and years (y-axis) over the pilot area.](image)

**Table 2** Correlation (r) and root mean square error obtained from second-order Gaussian fit between Julian days and soil moisture percentage in the pilot area

<table>
<thead>
<tr>
<th>Year</th>
<th>a1</th>
<th>b1</th>
<th>c1</th>
<th>a2</th>
<th>b2</th>
<th>c2</th>
<th>r</th>
<th>RMSE</th>
</tr>
</thead>
<tbody>
<tr>
<td>2002</td>
<td>24.09</td>
<td>172.8</td>
<td>21.42</td>
<td>15.92</td>
<td>211.7</td>
<td>27.53</td>
<td>0.914</td>
<td>2.938</td>
</tr>
<tr>
<td>2003</td>
<td>25.52</td>
<td>184.8</td>
<td>20.18</td>
<td>12.58</td>
<td>203.3</td>
<td>70.89</td>
<td>0.901</td>
<td>5.196</td>
</tr>
<tr>
<td>2004</td>
<td>22.09</td>
<td>174.3</td>
<td>20.77</td>
<td>11.7</td>
<td>210.2</td>
<td>88.31</td>
<td>0.879</td>
<td>4.415</td>
</tr>
<tr>
<td>2005</td>
<td>14.06</td>
<td>188.6</td>
<td>49.31</td>
<td>32.12</td>
<td>183.2</td>
<td>11.18</td>
<td>0.963</td>
<td>3.632</td>
</tr>
<tr>
<td>2006</td>
<td>–28.23</td>
<td>155</td>
<td>18.01</td>
<td>39.19</td>
<td>168.2</td>
<td>37.28</td>
<td>0.950</td>
<td>3.988</td>
</tr>
<tr>
<td>2007</td>
<td>20.48</td>
<td>179.2</td>
<td>13.56</td>
<td>15.19</td>
<td>194.5</td>
<td>43.57</td>
<td>0.965</td>
<td>2.685</td>
</tr>
<tr>
<td>2008</td>
<td>34.94</td>
<td>185.5</td>
<td>31.85</td>
<td>23.89</td>
<td>164.5</td>
<td>2.159</td>
<td>0.857</td>
<td>6.918</td>
</tr>
<tr>
<td>2009</td>
<td>27.13</td>
<td>191</td>
<td>18.03</td>
<td>5.908</td>
<td>203.10</td>
<td>280.10</td>
<td>0.913</td>
<td>4.527</td>
</tr>
<tr>
<td>2010</td>
<td>34.03</td>
<td>188.9</td>
<td>17.36</td>
<td>6.18</td>
<td>222.2</td>
<td>213.4</td>
<td>0.922</td>
<td>5.345</td>
</tr>
<tr>
<td>2011</td>
<td>78.83</td>
<td>210.7</td>
<td>40.33</td>
<td>–64.77</td>
<td>217.5</td>
<td>27.35</td>
<td>0.900</td>
<td>5.508</td>
</tr>
</tbody>
</table>

Gaussian model: \[ f(x) = a1 \exp(-((x-b1)/c1)^2) + a2 \exp(-((x-b2)/c2)^2) \]
179 JD) in the early soil moisture availability for agricultural practices during the 2004 to 2010 time period. Hence, the above results highlight a shift in the irrigation practices in the absence of rainfall due to implementation of the Water Act in 2009.

After the pilot area analysis of soil moisture, regional analysis for the states of Punjab and Haryana was done using maximum rate of soil moisture change ($SM_{\text{max}}$, first derivative of fitted soil moisture) which gives information about the time of field preparation and transplanting of

Figure 5 | (a) Second-order Gaussian fit and (b) rate of change of soil moisture during 140 JD to 240 JD for the years 2004 and 2010.
rice (Gupta et al. 2011), and corresponding JD were identified over the region. The average JD over the region for attaining $SM_{\text{max}}$, in the year 2004 was 172 with SD of 8 days (i.e., middle of June) whereas for the year 2010 it was 186 JD with SD of 5 days (i.e., start of July). Hence, an overall shift of about 2 weeks has been obtained over the study region. This shows a shift of crop calendar in the region due to the implementation of governmental sub-soil water policy since 2 April 2009, according to which no paddy nursery should be seen before May 10 and no practice of rice cultivation could be done before June 10 (Singh 2009). The variability in attaining the soil wetness in the case of the year 2004 is very high (coefficient of variability 0.42) due to the controlled and time variant agricultural practices as compared to the later period, i.e., 2010 (coefficient of variability 0.20).

Pre- and post-policy scenario

The temporal average of every alternate day soil moisture was done in the study area, both for the pre- (2002–2007) and post- (2009–2011) policy time frame. The maximum rate of soil moisture change ($SM_{\text{max}}$) was calculated for all the years and corresponding JD were written on a cell-by-cell basis over the study area. Dates (JD) of attaining maximum soil moisture change rate were averaged to prepare pre- (2002–2007) and post- (2009–2011) policy scenarios for the study area (Figure 6(a) and 6(b)).

It was estimated that there is a total of 2 weeks’ shift in attaining $SM_{\text{max}}$, between the pre- and post-policy implementation period in the pilot area. In the pre-policy time frame, the average days’ shift in attaining $SM_{\text{max}}$ was $175 \pm 2$ JD with minimum 171 JD and maximum 181 JD. Average days’ shift for $SM_{\text{max}}$ for the post-policy was $187 \pm 1$ JD with minimum 181 JD and maximum 191 JD. However, over the whole study area, average JD to attain $SM_{\text{max}}$ during pre-policy was $175 \pm 4$ JD with minimum 165 JD and maximum 187 JD whereas for the post-policy time frame it was $185 \pm 3$ JD with minimum 149 JD and maximum 193 JD, i.e., in total an overall 10 days’ shift over the region.

At the regional scale, we observed that in the pre-policy time frame spatial variability in JD was high (Figure 6(a)) compared to post-policy time frame (Figure 6(b)). Less variability in attaining the $SM_{\text{max}}$ in the post-policy time frame was due to the synchronization of rainfall and irrigation for rice cultivation as conceptualized for a rain-fed system (Figure 2(b)). However, in the pre-policy time frame, the
high variability in attaining $SM_{\text{max}}$, is attributed to the non-uniform rice plantation in response to the unregulated GW resource utilization.

Rainfall pattern analysis

Rainfall data of $0.25 \times 0.25$ degree spatial resolution obtained from the IMD were analysed in the pilot area as well as over the whole study region to check the rainfall contribution in the soil moisture pattern pre- and post-Water Act. From the year 2002 to 2011, the rainfall analysis shows onset of monsoon in the last week of June. However, few sporadic rainfall events were observed in 2007 and 2008 in the middle of June (Figure 7). From Figure 7 it can be seen that in the year 2004 effective rainfall was almost negligible until the end of July whereas in 2010 rainfall starts after the first week of July. During the negligible rainfall period for the years 2004 (pre-policy) and 2010 (post-policy) there was continuous increase in the early soil moisture (Figure 5(a)). This increase in soil moisture is thus only attributed to the shift in irrigation practices from pre- (163 JD) to post-policy (179 JD) implementation.

Correlation analysis between soil moisture and rainfall have strengthened our finding regarding shift in the early soil moisture due to the Water Act of 2009. A better correlation was observed between soil moisture and rainfall for the post-policy time frame ($r = 0.61$, Figure 8(a)) compared to pre-policy time frame ($r = 0.36$, Figure 8(b)). In the pre-policy time frame, soil moisture is mainly governed by irrigation along with sporadic rainfall events or without rainfall and results in less correlation between soil moisture and rainfall. In the post-policy time frame, soil moisture variation was largely dependent on rainfall along with minimum supplementary irrigation, and thus high correlation ($r$) was found.

Rainfall and soil moisture relation in pre- and post-policy time frame

The policy implementation effect was observed by passive microwave radiometry in pre- and post-policy scenarios both in the pre-monsoon phase and during the monsoon phase where the vegetation perturbation was minimum.
Figure 9(a) and 9(b) show the average soil moisture scenario in pre- and post-policy time frames (1–18 June). In the pre-policy time frame, soil moisture was found to be significantly high in the Punjab and Haryana region even in the absence (negligible) of rainfall (Figure 9(c)) which demonstrates the influence of irrigation as another source of soil moisture increment. However, in the post-policy time frame, both the soil moisture (Figure 9(b)) and rainfall (Figure 9(d)) was insignificant during June 1–18. This itself explains that the soil moisture source, i.e., irrigation, has been stopped after policy implementation. The soil moisture scenario during the monsoon period (1–18 July) was similar in both the pre- and post-policy scenario (Figure 9(e) and 9(f), respectively) and was found to be related with the rainfall pattern (Figure 9(g) and 9(h), respectively for pre- and post-policy scenario). Thus it may be concluded that the policy is effective. However, we have also observed that in a few situations, the timing of soil moisture (SMax) and onset of monsoon (OEM) are similar, say for example in the years 2005, 2006 and 2010. A special case was observed for the year 2002 (pre-policy) where OEM was very late (190 JD) and SMax was on 173rd JD. Early soil moisture emergence associated with late rainfall shows the influence of irrigation. For the year 2011 (post-policy), the monsoon was early (OEM = 168) even though the SMax was on 187th JD showing delayed rice cultivation in the post-policy scenario.

To further analyse the rainfall and soil moisture relationship we have correlated JDs for OEM and SMax in both the pre-policy and post-policy time frame (Figure 10(a) and 10(b)). We assume that if the rainfall is the only governing factor in soil moisture increment, there should be good correlation between the onset of rainfall and emergence of soil moisture in both the pre- and post-policy time frame. However, after analysis it was found that the correlation was much higher in the post-policy time frame ($r = 0.66$, Figure 10(b)) compared to the pre-policy time frame ($r = 0.31$, Figure 10(a)). This occurred because in the pre-policy time frame farmers started growing rice as early as possible using irrigation facilities without the dependency of monsoon rains while in the post-policy time frame, they started growing as suggested in the Punjab Water Act 2009. The shifting of rice phenology was also verified from observations of continuous shift in JD to attain NDViMax (232 for year 2002 and 247 for year 2011).

**Changes/shift in vegetation condition**

It is evident that crop growth follows a Gaussian curve trend. Peak NDVI (NDViMax from hereafter) is reached when the
Figure 10 | Relationship between OEM JD and SMmax for (a) pre-policy and (b) post-policy.

Figure 11 | Shift in mean NDVI during the study period (2002–2011) (tm = JD when NDVI is maximum).

Table 3 | First-order Gaussian coefficients, correlation (r) and standard error, maximum NDVI (NDVIm), Julian day (tm) and Julian calendar dates obtained from Gaussian fit between Julian days and NDVI

<table>
<thead>
<tr>
<th>Years</th>
<th>a</th>
<th>b</th>
<th>c</th>
<th>r</th>
<th>SEE</th>
<th>NDVIm</th>
<th>tm</th>
<th>tm</th>
</tr>
</thead>
<tbody>
<tr>
<td>2002</td>
<td>0.6658</td>
<td>231.95</td>
<td>49.02</td>
<td>0.97</td>
<td>0.6658</td>
<td>0.0508</td>
<td>231.95</td>
<td>19 Aug</td>
</tr>
<tr>
<td>2003</td>
<td>0.7401</td>
<td>230.39</td>
<td>45.81</td>
<td>0.98</td>
<td>0.7401</td>
<td>0.0498</td>
<td>230.39</td>
<td>18 Aug</td>
</tr>
<tr>
<td>2004</td>
<td>0.7263</td>
<td>229.82</td>
<td>48.88</td>
<td>0.99</td>
<td>0.7263</td>
<td>0.0355</td>
<td>229.82</td>
<td>17 Aug</td>
</tr>
<tr>
<td>2005</td>
<td>0.7648</td>
<td>234.33</td>
<td>48.23</td>
<td>0.98</td>
<td>0.7648</td>
<td>0.0475</td>
<td>234.33</td>
<td>22 Aug</td>
</tr>
<tr>
<td>2006</td>
<td>0.7736</td>
<td>234.94</td>
<td>45.18</td>
<td>0.98</td>
<td>0.7736</td>
<td>0.0514</td>
<td>234.94</td>
<td>22 Aug</td>
</tr>
<tr>
<td>2007</td>
<td>0.7043</td>
<td>235.59</td>
<td>50.24</td>
<td>0.95</td>
<td>0.7043</td>
<td>0.0779</td>
<td>235.59</td>
<td>23 Aug</td>
</tr>
<tr>
<td>2008</td>
<td>0.7439</td>
<td>241.75</td>
<td>47.31</td>
<td>0.99</td>
<td>0.7439</td>
<td>0.0337</td>
<td>241.75</td>
<td>29 Aug</td>
</tr>
<tr>
<td>2009</td>
<td>0.6777</td>
<td>243.4</td>
<td>53.68</td>
<td>0.98</td>
<td>0.6777</td>
<td>0.03515</td>
<td>243.4</td>
<td>31 Aug</td>
</tr>
<tr>
<td>2010</td>
<td>0.6439</td>
<td>248.7</td>
<td>54.33</td>
<td>0.89</td>
<td>0.6439</td>
<td>0.04601</td>
<td>248.7</td>
<td>5 Sep</td>
</tr>
<tr>
<td>2011</td>
<td>0.6517</td>
<td>246.7</td>
<td>53.71</td>
<td>0.95</td>
<td>0.6517</td>
<td>0.03879</td>
<td>246.7</td>
<td>3 Sep</td>
</tr>
</tbody>
</table>

Gaussian model: $y = a \exp(-{(b-x)^2)/(2c^2)})$
crop attains its maximum growth level. Figure 11 represents the shift in the mean NDVI (10-day composite) for all the years, i.e. 2002 to 2011, considering the June to November time period in the pilot area. Julian days for attaining the NDVImax for the years 2004 and 2010 are highlighted to represent pre- and post-Punjab Water Act 2009. The Gaussian model, year-wise coefficients, correlation (r) and standard error, time to peak, etc. are given in Table 3.

Model-based analysis indicates that NDVI peaked by 230 ± 5 JD in the year 2004 compared to 249 ± 5 JD in the year 2010. Thus it may be deduced that in the year 2004 the transplanting of rice started earlier compared to the year 2010 and a delay of about 3 weeks was obtained. Figure 12(a) and 12(b) show maximum NDVI distribution in the 0.01° × 0.01° cell over the Punjab and Haryana states for the year 2004 and 2010, respectively. Maximum NDVI values for the year 2004 and 2010 do not differ significantly, especially in the central Punjab region. However, the days at which NDVI reaches peak value have shown a noticeable shift (Figure 12(c) and 12(d)) for the year 2004 and 2010, respectively.

An overall shift of 5 weeks (237 ± 5 JD to 257 ± 5 JD) in attaining the peak NDVI was observed when the analysis was done at the regional level, i.e., states of Punjab and Haryana (Figure 12(c) and 12(d)). However, some anomalies have been observed in the soil moisture pattern due to the insensitivity of the AMSR-E sensor regarding the dense vegetation condition. Interestingly, passive microwave
radiometer loses its sensitivity to provide relatively precise data for the soil moisture by 206 to 220 JD (refer to Figure 4) whereas peak NDVI is obtained by 232 to 247 JD (refer to Figure 11), i.e., prior to 4 weeks of NDVI_max attainment by the crop. Oza et al. (2006) also studied passive microwave signal for soil moisture and concluded that signal saturates after 40% cover of the vegetation.

CONCLUSIONS

Punjab and Haryana regions of India have been associated with overexploitation of GW resources in the last one and a half decades. This has resulted in framing of government policies for the utilization as well as timing and use of GW resources. Due to this there has been a change in the irrigation practices over the region. Passive microwave (AMSR-E) and optical (SPOT-VGT) remote sensing from a satellite platform provided the opportunity to detect and monitor the shifting irrigation practices from the year 2002 to 2011 over the study region. The following conclusions may be drawn from this study:

(1) A shift of 2 weeks in the start of irrigation practices was observed in Punjab and Haryana states from 2002 to 2011.

(2) It has been found that patterns of early soil moisture were distinct during pre- (2002–2007) and post- (2009–2011) policy time.

(3) A similar phenomenon of delay in sowing practices was observed from SPOT NDVI data. Analysis of pre- and post-Water Act has demonstrated a delay of 2 weeks in attaining peak NDVI over the region.

(4) A high variability in irrigation/transplanting practices of rice has been observed over the study region in the early phase (pre-policy implementation) whereas in the later phase (post-policy), a more uniform irrigation/transplanting is obtained.

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